Int. J. Radiation Oncology Biol. Phys., Vol. 16, pp. 000–000
Printed in the U.S.A. All rights reserved

0360-3016/89 $3.00 + .00

● *Computer Applications*

THREE-DIMENSIONAL DISPLAY TECHNIQUES IN RADIATION THERAPY TREATMENT PLANNING

JULIAN ROSENMAN, PH.D., M.D.,[*] GEORGE W. SHEROUSE, M.S.,[*] HENRY FUCHS, PH.D.,[†]
STEPHEN M. PIZER, PH.D.,[*,†,‡] ANDREW L. SKINNER, B.S.,[†] CHARLES MOSHER, M.S.,[*,†]
KEVIN NOVINS, B.S.[*] AND JOEL E. TEPPER M.D.[*]

University of North Carolina at Chapel Hill

Good radiation treatment planning requires that the target volume be treated with a high and uniform dose of radiation while irradiating normal tissue as little as possible. Even if the merits of a given treatment plan are judged only on the appearance of isodose lines in one or a few planes it can sometimes be difficult for the experienced radiation oncologist to select the best of several alternative plans. If consideration is given to the entire spatial distribution of dose, however, the problem becomes far more difficult because of the enormous amount of data that must be evaluated. We believe that the lack of suitable methods to display these data has greatly contributed to the slow incorporation of 3D considerations into routine radiation treatment planning. In the past few years there have been great advances in both the theory of how to produce effective 3D displays and in the display hardware itself. In this paper we survey some of the methods used at the University of North Carolina, and show specific examples of how these displays can be used in radiation therapy treatment planning.

Treatment planning, Computer, Dose calculations, Computer graphics displays.

INTRODUCTION

The probability of eradicating most tumors is directly related to the radiation dose delivered (22). However, the safety of the treatment depends on how well normal tissue can be excluded from the high dose region. Thus to be safe and effective, the radiation dosage must be carefully matched to the target volume. Accordingly, good tumor target isodose conformity requires the solution of two related but distinct problems: accurate identification of the 3-dimensional (3D) target volume (tumor targeting), and selection of the spatial beam arrangement, weighting, and compensators that best protects normal tissue.

To perform tumor targeting with conventional simulation methods, the radiation oncologist must not only integrate the results of the physical examination, radiologic studies, and his knowledge of the pathways of tumor spread, but must accurately project this data onto a plane radiograph taking into account beam divergence. Not surprising, this transfer of information from various formats often proves to be extremely difficult; as a result even at the best institutions radiation oncologists often fail to adequately encompass the tumor in every radiation beam (23).

It can sometimes be difficult for an experienced radiation oncologist to select the best of several competing treatment plans even if consideration is given only to the dose distribution in one or a few planes. The problem becomes far more difficult if the entire spatial distribution of the radiation dosage is to be considered in judging the merits of a given plan. In this case the radiation oncologist can be overwhelmed by the amount of data to assimilate if the analysis must be done on a slice-by-slice basis. The ability to reconstruct CT data and display isodoses in sagittal, coronal, or arbitrarily obliqued planes can be a valuable in understanding 3 dimensional dose distributions as can techniques such as dose volume histogram analysis (1). However, it is our opinion that the lack of suitable methods to simultaneously display 3D dose distribution superimposed on the relevant anatomy has been a major factor in delaying the routine use of 3D therapy treatment planning.

Computed tomography (CT) is now generally considered essential for modern radiation therapy treatment

---

Presented at the ASTRO Annual Meeting, Boston, 1987.

Reprint requests to: Dr. Julian Rosenman, Department of Radiation Oncology, University of North Carolina at Chapel Hill, NC 27514.

[*] Department of Radiation Oncology.

[†] Department of Computer Science.

[‡] Department of Radiology.

This work was sponsored, in part, by a grant from the Whitaker Foundation.

Accepted for publication 27 July 1988.

planning (12). However conventional CT displays while providing detailed anatomic information imposes important limitations on the treatment planning process. First, this display format makes it difficult to visualize the path of any radiation beam not perpendicular to the axis of the CT slices. This discourages consideration of all treatment plans that utilize radiation beams out of the transverse plane. Second, by displaying the radiation isodoses on each CT slice, the merits of multiple competing treatment plans can be compared only in a piecewise fashion. Experience has shown that under these conditions it is not always easy either to recognize the best treatment plan or to suggest useful modifications (2). Finally, for brachytherapy treatment, the conventional CT format may offer ambiguous information as to the location of the implant; it may be impossible to determine whether a radioactive seed seen on one CT slice is the same as that seen on an adjacent slice.

We believe that these shortcomings of conventional CT displays can be largely overcome by the use of interactive 3D graphics displays. In the past few years there have been great advances in both the theory of how to produce effective 3D displays, and in the display hardware itself. This paper surveys some of the most important of these advances and reports on our preliminary experience in using these displays for tumor targeting and isodose surface display. Our preliminary experience with shaded graphics displays for brachytherapy has been published elsewhere (3, 4).

METHODS AND MATERIALS

Display of 3D anatomical structures from CT or MRI data sets is generally achieved by one of three methods. In the first, the surface-based display (6), the object of interest is modeled by many small polygons. In more sophisticated display techniques reflections of ambient light from surfaces, shadows, textures, and other effects are added to enhance the 3D effect. The production of high quality shaded graphics images from CT or MRI data currently requires many processing steps. The second method, direct voxel (volume element) display, gives the image a characteristic "sugar cube" appearance (8, 18). The third, and newest approach, is done entirely without polygons. A grey-scale shade and partial opacity is computed for each voxel in the data set. These values are blended along the viewing rays to form an image. By varying parameters of the shading computations, selected features can be enhanced or suppressed. This approach has been tentatively given the name volume rendering (11). At the University of North Carolina, we have historically concentrated on the use of surface-based displays for radiation therapy applications. However recently we have begun to explore the value of volume rendering. We believe that this approach, perhaps in combination with surface-based displays, holds enormous potential for radiation therapy. The use of direct [illegible] displays in radiation therapy have been reported elsewhere (8, 18) and will not be further discussed in this paper.

Object definition

Surface-based reflective methods require the user to define the contours or outline of the objects to be displayed. These objects can include normal anatomy, tumor, radiation target volumes, radioactive implants, radiation beams or radiation dosage levels. For high contrast objects such as bones it is frequently possible to define a range of pixel (picture element) intensities such that on each slice most pixels are non-ambiguously within or outside of the object in question. The object can then be automatically outlined (for example the bladder and rectum in Fig. 1). For low contrast objects, however, traditional edge-finding algorithms often fail, necessitating the use of manual outlining which can be exceedingly tedious. New approaches to define low contrast objects automatically, or interactively, after an automatic image description stage, appear promising (16).

Surface specification

The output from the contour defining software is an ordered set of pixels which defines the object contour on each slice. The next step is to construct a surface from these 2D contours. The simplest approach (10) is to assign a width to each contour equal to the inter-slice thickness thus defining a stack of ribbons which become the surface of the 3D object. A better approach, the Fuchs-Kedem-Uselton method (7), defines a continuous surface that is made up of polygons or tiles with vertices on adjacent contours. The polygons (usually triangles) are selected to be those that give a minimum surface area. This approach does not always work correctly if the object in question has branching surfaces as do, for example, the bronchi. However, we have developed automatic means, augmented by interactive editing, for defining which contours are to be connected to which (15).

Rendering of surfaces

Rendering is the process of computing and displaying the intensity and color of each screen pixel so as to give the impression of a solid object. Rendering begins with a specified viewpoint and involves determining which surfaces are visible at each screen pixel. Then the color and intensity of each pixel of the visible surface is determined by a lighting model based on the intrinsic color of the surface, its orientation, and distance to the light source and the simulated viewer. Several increasingly sophisticated lighting models are now in widespread use. One of the simplest, Gouraud shading (9), involves linearly interpolating the shading across each polygon from shadings computed at the polygon vertices. These vertex shadings, in turn are computed by averaging the normals to the polygon. A more sophisticated method, Phong shading (14), involves interpolating the normals rather than the shading; it has the advantage of allowing specular reflec-

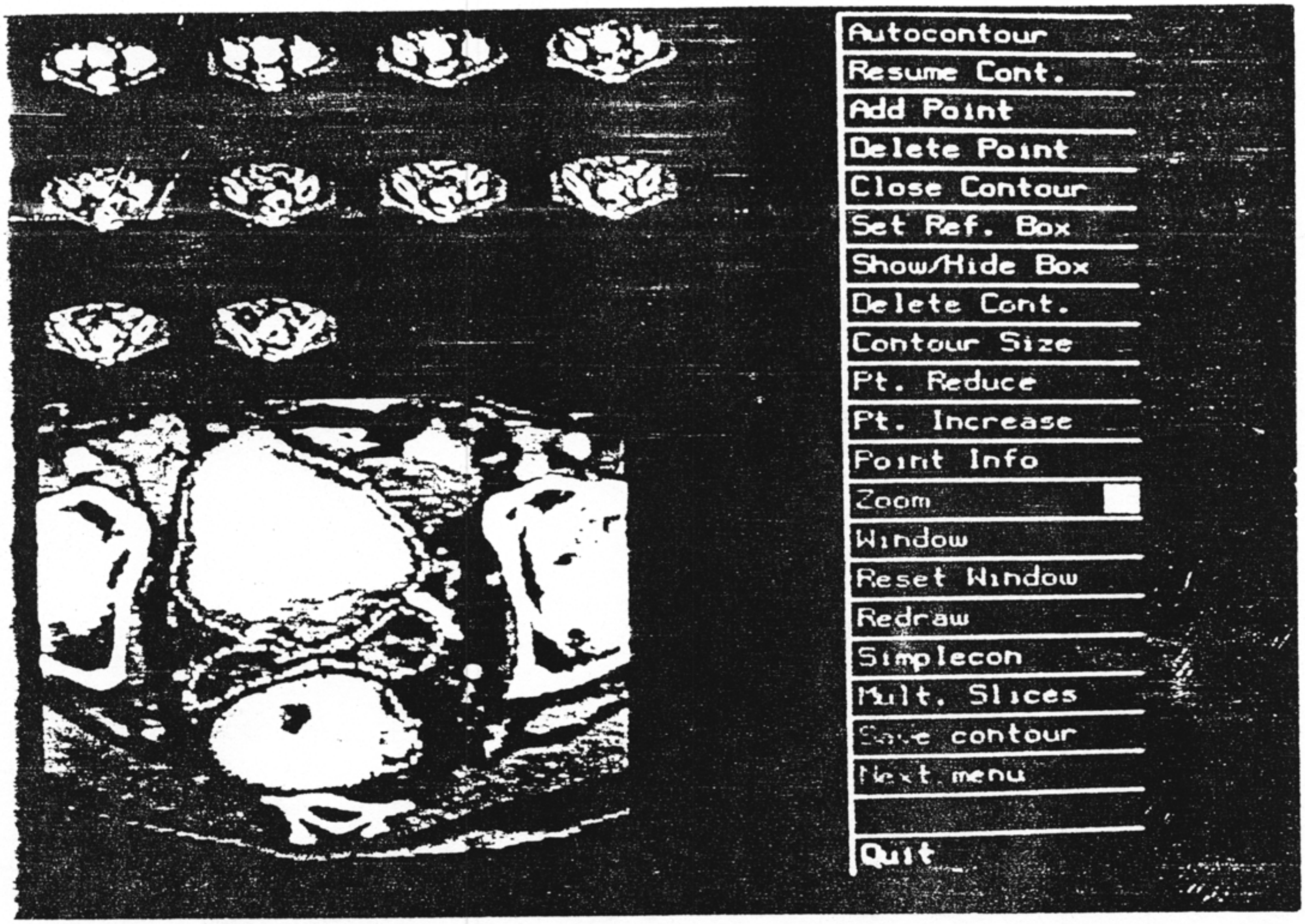

Fig. 1. The image editor (IMED) used to contour anatomy and tumors. The bladder and rectum have been automatically contoured, the seminal vesicles contoured by hand. The red dots have been manually or automatically placed, the green dots are interpolated values.

tions to be included. Sophisticated renderers allow more than one surface to be displayed at a given pixel; the intensities of the contributing surfaces are then combined to give the effect of transparency.

Volume rendering

Despite the high quality of presentation provided by surface-based methodologies, they all suffer from an inherent weakness: the objects of interest must be individually defined in some fashion. Thus, these methods cannot display previously unnoticed objects and, at least currently, require a large amount of complex preprocessing.* These images were created by assigning each voxel a probability that it is a certain tissue type, for example bone, muscle, or air. For example, a voxel can be partly bone and partly muscle. A certain color and transparency is assigned by the user for each tissue type. Each displayed pixel is assigned a composite of all the colors and transparencies that its ray encounters as it passes through the various voxels in the modeled volume. In addition, as the ray is projected into the volume, whenever an object surface appears to be encountered some surface shading model is applied—giving the appearance of shininess on the object surfaces. An independent technique for doing similar volume rendering has been developed by one of our graduate students (11).

RESULTS

Figure 1 is an example of the object definition, necessary for surface based displays. The CT scan has been generated from a patient with prostatic cancer. The bladder and the rectum have been automatically contoured; this was possible because of the significant contrast between the structures and adjacent structures. The seminal vesicles, how-

---

* High quality images based on projection of image densities, were first demonstrated by Pixar, Inc., San Rafael, CA.

Fig. 2. A lung cancer targeted with a radiation beam. Shown are the external surface, lungs, and the tumor. This is an example of a Phong shaded image.

ever, have low contrast with the all adjacent soft tissue, and thus tedious manual contouring has been necessary.

Figure 2 is a Phong rendered, surface-based shaded graphics display created from the CT scans of a young female patient with lung cancer. Shown are the external contours, lungs, and tumor. A radiation boost field is placed over the tumor. If both the rendered image and the radiation field were fully interactive in real-time it is clear that we would have a powerful technique for tumor targeting and radiation portal design. A prototype of such computer aided design (CAD) software is now running in our Department of Radiation Oncology (13, 19, 20).

Figure 3a and 3b show a second important use of high quality shaded graphics images; displaying a 3D radiation dose distribution. Medial and lateral tangential fields have been set up with the intention of providing a homogeneous treatment to the entire breast. One can visualize the dose to the entire treatment volume, not just one transverse plane at a time. The isodose surfaces demonstrate that the breast treatment is substantially underwedged; as a result, volumes of the breast are receiving 130% or more of the prescribed dose. These pictures have been made into a "film-loop" which shows the isodose surfaces changing from 70 to 140%. As they change values, the color of the isodose surfaces changes from white to bright red, allowing the physician to rapidly pick out volumes with excess dose.

Figure 4a and 4b show the isodose surfaces from a typical three-field treatment of esophageal cancer (anterior, right posterior oblique, and left posterior oblique) using 4 MV X rays. The 95% isodose surface pinches in dramatically in the center of the field causing a cold spot. This might have been missed entirely if the doses were examined on only a few CT slices. When transferred to improved hardware we should be able to interactively rotate the image and display the desired isodose surface in real time.

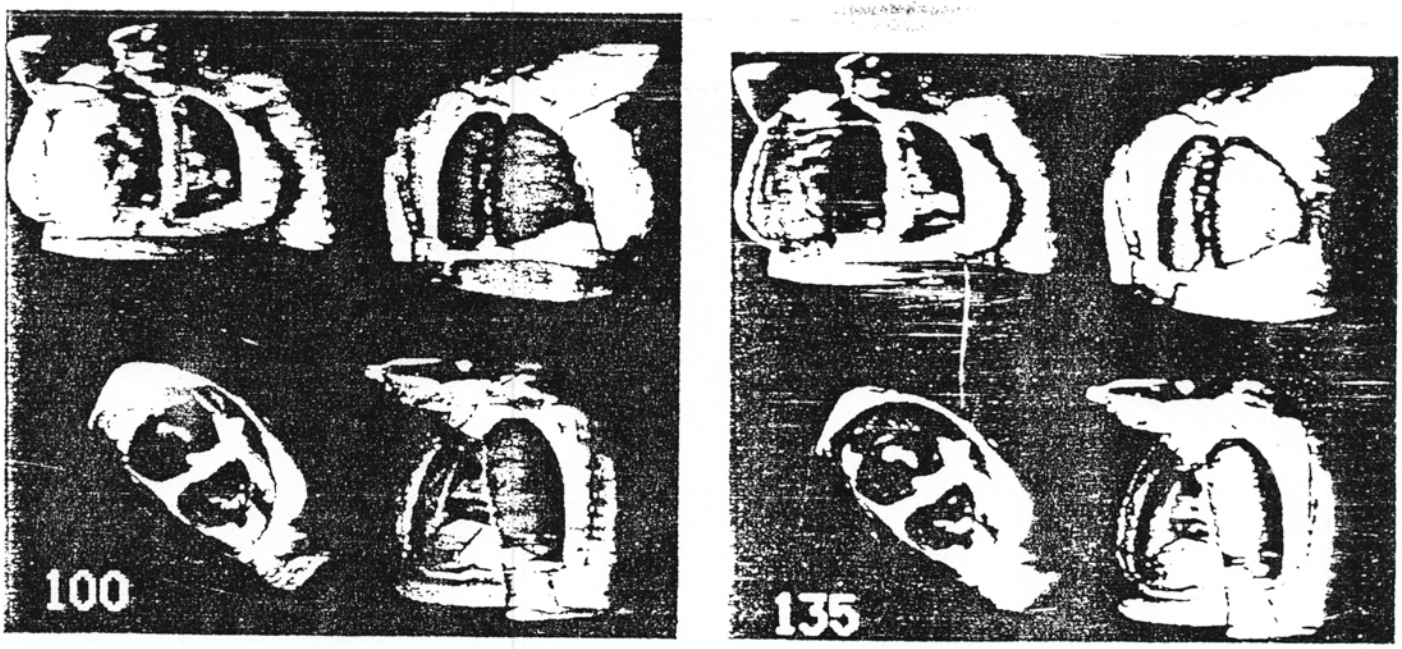

Fig. 3. (a) The 100% isodose surface from a tangential beam setup for the treatment of breast cancer (pink). Shown are an AP, posterior oblique, transverse and lateral view. The white object in the center of the lower left image is the underside of the patient's head and nose. (b) The 135% isodose surface of the same set up as in Fig. 3a. Notice the unexpectedly "ragged" distribution of dose seen in the upper left hand view. Such a distribution would be hard to understand if displayed only on conventional CT slices.

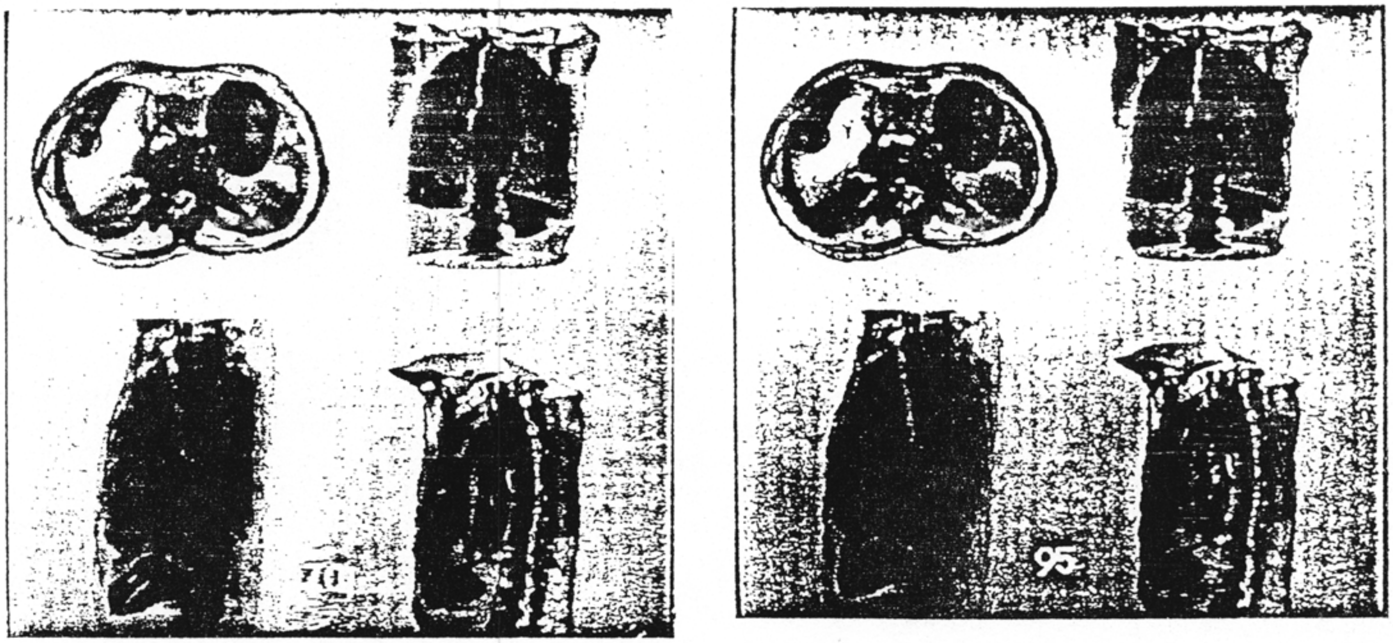

Fig. 4. (a) The 70% isodose surface of a 3-field esophageal treatment set up on a 4 MV linear accelerator. Shown are transverse, AP lateral and oblique views. The blue is esophagus and stomach, the yellow is spinal cord. Notice in the upper right hand view how the dose would be underestimated if calculated on the central plane only. (b) The 95% isodose surface of the same set up as in (a).

The images of Figure 5 were produced by the Levoy volume rendering approach taken from CT scan data of a cadaver. No polygons or other geometric primitives are involved. All four views were generated from 106, 2 mm thick CT slices. The top and bottom pairs differ only in the parameters used to choose the voxels of interest. Thus without any manual contouring one is able to view the skin surface (top pair) and compare it to the bony surface

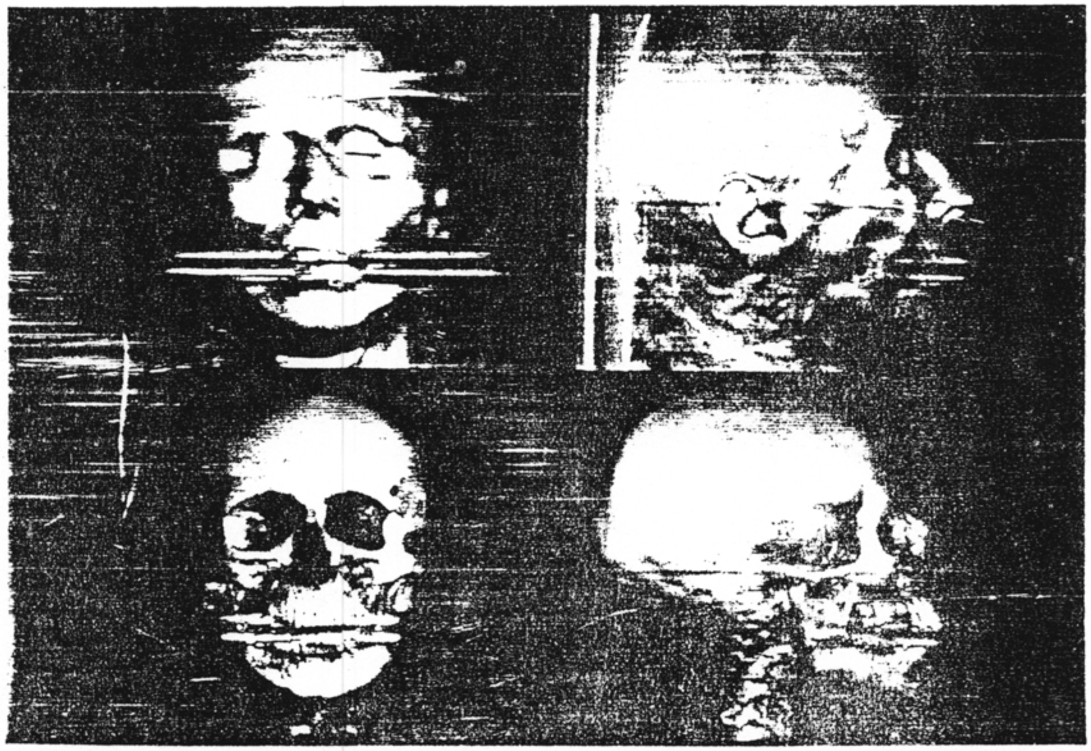

Fig. 5. Levoy's volume rendering from CT scans of a cadaver. The artifact in the area of the mouth is from dental fillings. The band across the forehead is tape that was used to hold the body in place. Such images now take less than 5 minutes each to produce; our goal is to [illegible] allow for real-time interaction.

(bottom pair). The picture quality is so good that one can visualize the tape placed across the forehead of the cadaver. Each of these images can at present be produced on a SUN 4 workstation in less than 5 minutes. Methods to produce such images in near real time are under active investigation at our institution.

DISCUSSION

Three-dimensional image display techniques are not new, but the software and hardware necessary to produce them has only now become sufficiently refined to make them clinically useful. Unfortunately most physicians do not have ready access to the journals and proceedings in which these advances are usually published. One of the goals of this paper, then, is to survey some of the most important display techniques and show how they can be applied to radiation therapy planning at the University of North Carolina.

Although we have developed very efficient rendering software it still requires up to an hour of CPU time on a VAX 11/750 to produce a fully rendered image such as that in Figure 2. We believe that the real value of these images for the radiation oncologist can be realized only if real-time interaction with the images is possible. For this to happen the rendering time must be cut from 1 hour to a fraction of a second, an increase in speed of about 10,000 times. Such speed in computation is beyond the reach of even the most powerful general purpose computers.

However real-time interaction with shaded graphic images is now possible with special hardware. Fuchs and colleagues have developed such a machine, a processor-per-pixel custom graphics engine in our Computer Science Department (5, 6, 17). This machine, named "Pixel-planes" was completed in August 1986; a newer, faster and more capable version is under construction. Pixel-planes is actually a collection of 100,000, or so tiny computers working independently of each other, and is capable of displaying high quality surface-based displays that can be manipulated in real-time (specifically, about 35,000 smooth shaded z-buffered triangles per second). Commercial computers are now becoming available with capabilities approaching the 1986 version of Pixel-planes. This is very important, because it means that our work will no longer be confined to graphics laboratories, but can be moved directly into the clinical arena.

In this paper we have discussed the role of 3D shaded graphics in understanding spatial radiation dose distributions. As is shown in Figure 3b (upper left), for example, that distribution can sometimes be very irregular. We feel that such an "understanding at a glance" is necessary to keep the clinician from becoming bogged down in endless details as he would be if provided only with conventional CT displays with overlayed isodose lines. This is not to state that surface based displays can totally replace conventional CT displays, but rather to suggest that both are necessary if 3D treatment planning is to become feasible on a routine clinical basis.

Affordable hardware is now becoming available to make rapid production of high quality surface based displays possible. However, significant problems still remain with the surface-based approach, the most important of these being the automation of low contrast object definition. The volume rendering technique may overcome some of the shortcomings of surface-based displays as the final image does not depend on object definition (although it does depend on user selection of some parameters). However it is not yet clear when hardware can be built that would allow the images to be fully interactive. In addition it has not yet been demonstrated that volume rendering will be successful in displaying soft tissue.

One display approach that we find promising is that of combining volume rendering with surface-based displays. If this proves feasible one could use the exquisite bony detail provided by volume rendering as a background for a surface-based display of the target volume or isodose surface. This eliminates the need for most anatomic object definition while preserving the advantages of surface based display for isodose surfaces.

Radiation treatment planning has come a long way since the days when doses were hand calculated. Sherouse (21) has identified four generations of computerized radiation therapy treatment planning. The first generation used 2-dimensional contours only, and calculated the radiation doses by interpolating from stored data. Typically the input was through a deck of punch cards and the program was run in batch mode.

After the early 1970's it became possible for large radiation oncology centers to own their own computer system and run their programs interactively. With these systems one could begin to "experiment" by generating several treatment plans and selecting the best one. The standard model was still a single outline obtained by manual contouring, but now more precisely digitized and displayed.

In the late 1970's, with the widespread use of CT one could obtain very precise maps of the geometry of the patient. Three dimensional dose calculation software became available and the radiation oncologist now found himself in the unaccustomed position of having too much data to comprehend. The advent of software and hardware that allows the physician to manipulate 3D models of the patient marks the beginning of the fourth generation of radiation treatment planning. With this advanced technology the physician will be able to comprehend the benefits and shortcomings of a given 3 dimensional treatment plan. As a result he should be able to generate innovative plans which could not previously be understood with confidence.

It is important to view the use of 3D display technology as a logical evolutionary step in the history of radiation therapy treatment planning. The machines that will make this type of system possible are beginning to appear on the commercial market. The radiotherapy community should make the effort to utilize these technological advances to optimize patient care.

REFERENCES

1. Austin-Seymour, M. M.; Chen, G. T. Y.; Castro, J. R.; Saunders, W. M.; Pituck, S.; Woodruff, K. H.; Kessler, M. L. Dose volume histogram analysis of liver radiation tolerance. Int. J. Radiat. Oncol. Biol. Oncol. Phys. 12:31–35; 1986.
2. Bauer-Kirpes, B.: Schlegel, W.; Boesecke, R.; Lorenz, W. J. Display of organs and isodoses as shaded 3-D objects for 3-D therapy planning. Int. J. Radiat. Oncol. Biol. Phys. 13: 135–140; 1987.
3. Bourland, D.; Chaney, E.; Fuchs, H.; Mahaley, S.; Naves, J.; Pizer, S.; Rosenman, J.; Sherouse, G.; Staab, E.; Varia, M.; Whaley, R. 3D treatment planning from CT scans using fast interactive shaded graphics (Abstr.). Int. J. Radiat. Oncol. Biol. Phys. 11(Suppl. 1):164; 1985.
4. Chaney, E.; Rosenman, J.; Sherouse, G.; Bourland, D.; Fuchs, H.; Pizer, S.; Staab, E.; Varia, M.; Mahaley, S. Three-dimensional displays of brain and prostate implants. Endo./Hyperther. Oncol. 2:93–99; 1986.
5. Fuchs, H.; Goldfeather, J.; Hultquist, J. P.; Spach, S.; Austin, J. D.; Eyles, J. G.; Poulton, J. Fast spheres, shadows, textures, transparencies, and image enhancements in Pixel-planes. Comp. Graph. 19:111–120, Proc. 1985 SIG-GRAPH Conference, 1983.
6. Fuchs, H.; Kedem, Z. M.; Uselton, S. P. Optimal surface reconstruction from planar contours. Comm. ACM 20:693–702; 1977.
7. Fuchs, H.; Poulton, J. W. Pixel-planes: A VLSI-oriented design for a raster graphics engine. VLSI Design 2:20–28; 1981.
8. Goldwasser, S. M. The voxel processor architecture for real-time display and manipulation of 3D medical objects. Proc. 6th NCGA Conference 3:71–80; 1985.
9. Gouraud, H. Continuous shading of curved surfaces. IEEE Trans. Comp. 20:623–628; 1971.
10. Herman, G. T.; Liu, H. K. Three-dimensional display of human organs from computer tomograms. Comp. Graph. Image Proc. 9:1–21; 1979.
11. Levoy, M. Rendering of surfaces from volumetric data. Technical Report 87-016, Dept. of Computer Science, Univ. of North Carolina, Chapel Hill, 1987.
12. Ling, C. C.; Rogers, C. C.; Morton, R. J. Computed tomography in radiation therapy. New York: Raven Press; 1983.
13. Mosher, C.; Sherouse, G.; Mills, P.; Novins, K.; Pizer, S.; Rosenman, J.; Chaney, E. The virtual simulator. Proc of the 1986 workshop on interactive 3D computer graphics. ACM Publication #429861.
14. Phong, B. T. Illumination for computer generated images. Ph.D. Dissertation, University of Utah, 1973.
15. Pizer, S. M.; Fuchs, H.; Mosher, C.; Lifshitz, L.; Abram, G. D.; Ramanathan, S.; Whitney, B. T.; Rosenman, J. G.; Staab, E. V.; Chaney, E. L.; Sherouse, G. 3D shaded graphics in radiotherapy and diagnostic imaging. Proc. computer graphics '86, National Computer Graphics Association III. 1986; 107–113.
16. Pizer, S.; Oliver, W.; Gauch, J.; Bloomberg, S. Hierarchical figure-based shape description for medical imaging. Proc NATO advanced science institute on mathematics and computer science in medical imaging. NY: Springer-Verlag; 1987.
17. Poulton, J.; Fuchs, H.; Austin, J.; Eyles, J.; Greer, T. Building a 512 × 512 Pixel-planes system. In: Losleben, P. ed. Proc of the 1987 Stanford Conference in Advanced Research in VLSI. Boston, MA: MIT Press; 1987:57–71.
18. Reynolds, R. A.; Gordon, D.; Chen, L. S. A dynamic screen technique for shaded graphics display of slice-represented objects. Comp. Vis. Graph. Image Proc. 38:275–298; 1987.
19. Sherouse, G.; Mosher, C. User interface issues in radiotherapy CAD software. Proc. 9th ICCR. 1987:429–432.
20. Sherouse, G.; Mosher, C.; Novins, K.; Rosenman, J.; Chaney, E. Virtual simulation: concept and implementation. Proc. 9th ICCR. 1987:433–436.
21. Sherouse, G. W. Radiation therapy workstations. Presented at the 1987 AAPM summer school on image communication and image analysis, Ann Arbor, Michigan; 1987:239–258.
22. Tepper, J. Clonogenic potential of human tumors, a hypothesis. Acta Radiol. Oncol. 20:283–288; 1981.
23. Tepper, J. E.; Padikal, T. N. The role of computed tomography in treatment planning. In: Bleehen, N. M., Glatstein, E., Haybittle, J. L., eds. Radiation therapy planning. NY: Marcel Dekker; 1983:139–158.